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13. ABSTRACT (Maximum 200 words)

The main goal of the project was to study theoretically the process of continuous measurement and feedback control of solid-state qubits, and to analyze possible use of quantum feedback for decoherence suppression. This initial goal has been somewhat extended in the course of the project and also included theoretical analysis of the RF-SET operation and close collaboration with experimental group at JPL on superconducting qubits. The obtained results have been published in 9 journal papers (2 more submitted) and 7 conference proceedings and book chapters.

1) We have developed the theory of continuous measurement of solid-state qubits and applied it to various setups, including entangled qubits, nanomechanical resonators, realistic nonideal detectors, and quadratic detectors. We have studied one-qubit quantum feedback and calculated the degree of decoherence suppression and state purification provided by the feedback. We have shown that the qubits can be made almost 100% entangled by continuous measurement, in spite of external decoherence. Several experiments have been proposed. 2) We have developed the theory of the response and sensitivity of the normal-metal RF-SET with realistically large Q-factor, and also proposed a new operation mode of the RF-SET. 3) We have been involved in collaboration with experimental group of Dr. Echternach (JPL) on observation of Rabi oscillations in the single-Cooper-pair-box qubit. Our contribution included development of the computer code for fitting experimental results, geometrical modeling of the sample design using FASTCAP, and theoretical support in a course of experiment.

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The problems studied in the course of the project

The main goal of the project was to study theoretically the process of continuous measurement of solid-state qubits and gradual purification of the qubit state due to continuous measurement, and to analyze possible use of quantum feedback control for decoherence suppression. The idea was that continuous monitoring of qubits is capable of sensing the gradual change of the qubit state due to decoherence, while the knowledge of this change can then be used in a feedback way to undo the change. In the simplest case this idea can be applied to maintain a desired state of a qubit or a system of qubits, in spite of external decoherence; in a quantum computer this can be used for initialization of qubits. A more advanced application of this idea (which was outside of this project scope) is continuous quantum error correction. A very important issue for continuous monitoring of qubits is the quantum back-action. However, the magnitude of this back-action can be extracted from the noisy record of continuous measurement, and therefore, the back-action can also be undone by quantum feedback.

To study the decoherence suppression by quantum feedback, we had to develop first the theory of continuous quantum measurements, which relates the quantum back-action and information contained in the continuous noisy output of the detector, which is available to an experimentalist (complete information on the qubit state would mean its complete purification, even starting from an unknown mixed state). This theory has been initially developed for measurement of a single solid-state qubit and then generalized to various measurement setups, including two and more entangled qubits (as a by-product, it has been also applied to nanomechanical resonators); a special study has been carried out to take into account features of realistic solid-state detectors, including various kinds of non-ideality (imperfect efficiency) and nonlinearity.

The theory of continuous quantum measurements has been applied to the analysis of quantum feedback and calculation of its operation fidelity in presence of decoherence. These studies resulted in the quantitative description of decoherence suppression by feedback. A special attention has been paid to the limitations of realistic experimental realizations, including finite bandwidth and finite delay in signal processing. We have also studied the ways to simplify the operation of quantum feedback, though for a price of reducing its fidelity.

We have proposed several experiments which would verify the possibility of quantum feedback and would eventually be useful for an operation of a quantum computer. In particular, we have proposed a Bell-type experiment verifying the possibility to monitor gradual evolution of a qubit, an experiment on producing entangled qubits by their continuous measurement, and several experiments on realization of one-qubit quantum feedback (from simple but imperfect to practically perfect but quite difficult). As a by-product, we have also proposed an experiment on squeezing the nanoresonator state, which can be useful for ultrasensitive force detection beyond the standard quantum limit.

Besides accomplishing the study planned for this project practically in full, we have extended the initial goal to include two more subjects. In order to analyze the operation of a realistic detector of solid-state qubits, we have developed the theory of response and sensitivity of the normal-metal radio-frequency single-electron transistor (RF-SET) with realistically large Q-factor. We have also proposed a new operation mode of the RF-SET based on its nonlinearity; in this mode the frequency of the reflected rf signal differs from the frequency of incoming wave, so that their separation becomes quite simple; the proposed mode has been successfully tested experimentally. As one more extension of initial plans, we have been involved in

collaboration with experimental group of Dr. Echternach (JPL) on observation of Rabi oscillations in the single-Cooper-pair-box qubit. Our contribution included development of the computer code for fitting experimental results, geometrical modeling of the sample design using FASTCAP, and theoretical support in a course of experiment. The group of Dr. Echternach has successfully demonstrated the Rabi oscillations in 2003 (for the first time in US for a superconducting charge qubit).

Summary of most important results

The obtained results have been published in 9 journal papers (2 more have been submitted) and 7 conference proceedings and book chapters.

- We have proposed a solid-state experiment to study the process of continuous quantum measurement of a qubit state. The experiment would verify that an individual qubit stays coherent during the process of measurement (in contrast to the gradual decoherence of the ensemble-averaged density matrix) thus confirming the possibility of the qubit purification by continuous measurement. The experiment can be realized using quantum dots, single-electron transistors, or SQUIDs. [A.N. Korotkov, Phys. Rev. B 64, 193407 (2001).]

- We have developed Bayesian formalism to describe the process of continuous measurement of entangled qubits. We have started with the case of two qubits and then generalized it to an arbitrary number of qubits. [A.N. Korotkov, Phys. Rev. A **65**, 052304, (2002).]

- We have studied theoretically the basic operation of a quantum feedback loop designed to maintain a desired phase of quantum coherent oscillations in a single solid-state qubit. The degree of oscillations synchronization with external harmonic signal has been calculated as a function of feedback strength, taking into account available bandwidth and coupling to environment. The feedback can efficiently suppress the dephasing of oscillations if the qubit coupling to the detector is stronger than coupling to environment. [R. Ruskov and A.N. Korotkov, Phys. Rev. B **66**, 041401(R) (2002).]

- We have shown that two identical solid-state qubits can be made fully entangled (starting from completely mixed state) with probability 1/4 just by measuring them with a detector, equally coupled to the qubits. This happens in the case of repeated strong (projective) measurements as well as in a more realistic case of weak continuous measurement. In the latter case the entangled state can be identified by a flat spectrum of the detector shot noise, while the non-entangled state (probability 3/4) leads to a spectral peak at the Rabi frequency with the maximum peak-to-pedestal ratio of 32/3. [R. Ruskov and A.N. Korotkov, Phys. Rev. B **67**, 241305(R) (2003).]

- We have developed the formalism suitable for calculation of the output spectrum of a detector continuously measuring quantum coherent oscillations in a solid-state qubit, starting from microscopic generalized Bloch equations. The results coincide with that obtained using Bayesian and master equation approaches. The previous results have been generalized to the

cases of arbitrary detector response and finite detector temperature. [R. Ruskov and A.N. Korotkov, Phys. Rev. B **67**, 075303 (2003).]

• The Bayesian formalism for a continuous measurement of solid-state qubits has been extended to a model which takes into account several factors of the detector nonideality. In particular, we have considered additional classical output and backaction noises (with finite correlation), together with quantum-limited output and backaction noises, and have taken into account possible asymmetry of the detector coupling. The formalism has been first derived for a single qubit and then generalized to the measurement of entangled qubits. [A.N. Korotkov, Phys. Rev. B **67**, 235408 (2003).]

• We have analyzed the response and noise-limited sensitivity of the radio-frequency single-electron transistor (RF-SET), extending the previously developed theory to the case of arbitrary large quality factor Q of the RF-SET tank circuit. It has been shown that while the RF-SET response reaches the maximum at Q roughly corresponding to the impedance matching condition, the RF-SET sensitivity monotonically worsens with the increase of Q. Also, we have proposed an operation mode, in which an overtone of the incident rf wave is in resonance with the tank circuit. [V.O. Turin and A.N. Korotkov, Appl. Phys. Lett. **83**, 2898 (2003); Phys. Rev. B **69**, 195310 (2004).]

• In collaboration with a group from SUNY, Stony Brook, we have developed a theory of quadratic quantum measurements by a mesoscopic detector. It has been shown that the quadratic measurements should have non-trivial quantum information properties, providing, for instance, a simple way of entangling two non-interacting qubits. We have also calculated the output spectrum of a quantum detector with both linear and quadratic response continuously monitoring coherent oscillations in two qubits. [W. Mao, D.V. Averin, R. Ruskov, and A.N. Korotkov, Phys. Rev. Lett. **93**, 056803, (2004).]

• We have proposed an experiment on quantum feedback control of a solid-state qubit, which is almost within the reach of the present-day technology. Similar to the earlier proposal, the feedback loop is used to maintain the coherent oscillations in a qubit for an arbitrary long time; however, this is done in a significantly simpler way, which requires much smaller bandwidth of the control circuitry. The main idea is to use the quadrature components of the noisy detector current to monitor approximately the phase of qubit oscillations. The price for simplicity is a less-than-ideal operation: the fidelity is limited by about 95%. The feedback loop operation can be experimentally verified by appearance of a positive in-phase component of the detector current relative to an external oscillating signal used for synchronization. [A.N. Korotkov, cond-mat/0404696.]

• In collaboration with Dr. Keith Schwab (LPS, College Park, MD) we have shown that the nanoresonator position can be squeezed significantly below the ground state level by measuring the nanoresonator with a quantum point contact or a single-electron transistor and applying a periodic voltage across the detector. The mechanism of squeezing is basically a generalization of quantum nondemolition measurement of an oscillator to the case of continuous measurement by a weakly coupled detector. The quantum feedback is necessary to prevent the "heating" due to

measurement back-action. We have also discussed a procedure of experimental verification of the squeezed state. [R. Ruskov, K. Schwab, and A.N. Korotkov, cond-mat/0406416.]

- The performance of a quantum feedback loop designed to maintain a desired phase of quantum coherent oscillations in a single solid-state qubit has been analyzed using the quantum Bayesian formalism. The degree of oscillations synchronization with classical reference signal has been calculated as a function of feedback strength, taking also into account finite detector bandwidth, dephasing due to environment, and qubit energy asymmetry. [R. Ruskov, Q. Zhang, and A.N. Korotkov, Proceedings of the 42th IEEE conference on Decision and Control, p. 4185 (2003); SPIE International Symposium on Defense and Security, Quantum Information and Computation, Proceedings of SPIE, vol. 5436, p. 162 (2004).]

- We have been involved in collaboration with Dr. Pierre Echternach and his postdoc Alexandre Guillaume (JPL, Pasadena, CA) on observation of the Rabi oscillations in a single-Cooper-pair box (SCPB), using an RF-SET nearby to measure the oscillating charge at the box. Besides extensive participation in discussions in a course of experimental work, we have developed a computer code intended to be used to fit experimental results to the theory. This code takes into account several kinds of single-electron and single-Cooper-pair processes in the SCPB; in contrast to simpler approaches, the code explicitly treats 4 charge states of the SCPB, since all 4 states are important during the pulsed operation of the device. We have also been involved in the layout design for the second round of experiments. Using FASTCAP package we have calculated the capacitance matrix of the structure from the design geometry; this has been done several times in the iterative way in order to choose the best geometry.

List of all publications and technical reports supported under this grant

(a) Papers published in peer-reviewed journals

1. A. N. Korotkov, "Correlated quantum measurement of a solid-state qubit", Phys. Rev. B **64**, 193407, pp. 1-4 (2001).

2. A. N. Korotkov, "Continuous measurement of entangled qubits", Phys. Rev. A **65**, 052304, pp. 1-5 (2002).

3. R. Ruskov and A. N. Korotkov, "Quantum feedback control of a solid-state qubit", Phys. Rev. B **66**, 041401(R), pp. 1-4 (2002).

4. R. Ruskov and A. N. Korotkov, "Entanglement of solid-state qubits by measurement", Phys. Rev. B **67**, 241305(R), pp. 1-4 (2003).

5. R. Ruskov and A. N. Korotkov, "Spectrum of qubit oscillations from Bloch equations", Phys. Rev. B **67**, 075303, pp. 1-8 (2003).

6. A. N. Korotkov, "Nonideal quantum detectors in Bayesian formalism", Phys. Rev. B **67**, 235408, pp. 1-11 (2003).

7. V. O. Turin and A. N. Korotkov, "Analysis of the radio-frequency single-electron transistor with large quality factor", Appl. Phys. Lett. **83**, 2898-2900 (2003).

8. V. O. Turin and A. N. Korotkov, "Numerical analysis of radio-frequency single-electron transistor operation", Phys. Rev. B **69**, 195310, pp. 1-13 (2004).

9. W. Mao, D. V. Averin, R. Ruskov, and A. N. Korotkov, "Mesoscopic quadratic quantum measurements", Phys. Rev. Lett. **93**, 056803, pp. 1-4 (2004).

(b) Papers published in non-peer-reviewed journals or in conference proceedings

1. R. Ruskov and A. N. Korotkov, "Quantum feedback control of a solid-state qubit", in: *Quantum Confinement VI: Nanostructured Materials and Devices*, edited by M. Cahay, J. P. Leburton, D. J. Lockwood, S. Bandyopadhyay, and J. S. Harris (Electrochemical Society, Pennington, N.J., 2001), pp. 287-297.

2. A. N. Korotkov, "Bayesian measurement of a single-Cooper-pair qubit" *International Workshop on Superconducting Nano-Electronic Devices*, edited by J. Pekkola, B. Ruggiero, and P. Silvestrini (Kluwer, N.Y., 2002), pp. 11-13 (invited talk).

3. A. N. Korotkov, "Noisy quantum measurement of solid-state qubits: Bayesian approach"; in *Quantum Noise in Mesoscopic Physics*, edited by Yu.V. Nazarov (Kluwer, Netherlands, 2003), pp. 205-228.

4. "Noisy quantum measurement of solid-state qubits", *SPIE's first international symposium on Fluctuations and Noise* (Santa Fe, NM, June 2-4, 2003), Proceedings of SPIE, v. 5115, pp. 386-400 (invited talk).

5. R. Ruskov, Q. Zhang, and A. N. Korotkov, "Quantum feedback control of coherent oscillations in a solid-state qubit", *42th IEEE conference on Decision and Control (CDC'03)* (Maui, HI, December 9-12, 2003), Proceedings, pp. 4185-4190.

6. R. Ruskov and A. N. Korotkov, "Quantum feedback control of solid-state qubits and their entanglement by measurement", *12th International symposium Nanostructures: Physics and Technology* (St. Petersburg, Russia, June 21-25, 2004), Proceedings, pp. 178-188.

7. R. Ruskov, Q. Zhang, and A. N. Korotkov, "Maintaining coherent oscillations in a solid-state qubit via continuous quantum feedback control", *SPIE International Symposium on Defense and Security, Quantum Information and Computation* (Orlando, FL April 12-14, 2004), Proceedings of SPIE, vol. 5436, pp. 162-171.

(c) Papers presented at meetings, but not published in conference proceedings

1. A. N. Korotkov, "Bayesian quantum measurement of a qubit", *5th International symposium on new phenomena in Mesoscopic structures* (Waikoloa, HI, Nov. 25-30, 2001), Abstracts, p. 6.

2. R. Ruskov and A. Korotkov, "Quantum feedback control of single and entangled qubits", *APS March Meeting* (Indianapolis, IN, March 18-22, 2002), Bulletin of APS 47, No. 1, p. 1083.

3. R. Ruskov and A. N. Korotkov, "Continuous feedback control of single and entangled qubits", *International Quantum Electronics Conference* (Moscow, Russia, June 22-27, 2002), Technical digest, p. 451.

4. R. Ruskov, A. N. Korotkov, W. Mao, and D. V. Averin, "Quadratic quantum detection", *APS March Meeting* (Austin, TX, March 3-7, 2003), Bulletin of APS 48, No. 1, p. 369.

(d) Manuscripts submitted, but not yet published

1. A. N. Korotkov, "Simple feedback of a solid-state qubit", cond-mat/0404696, submitted to Phys. Rev. B.

2. R. Ruskov, K. Schwab, and A. N. Korotkov, "Quantum Nondemolition Squeezing of a Nanomechanical Resonator", cond-mat/0406416, submitted to IEEE Trans. Nanotechnology.

(e) Technical reports submitted to ARO

- Interim Progress Report for year 2001
- Interim Progress Report for year 2002
- Interim Progress Report for year 2003
- copies of publications

List of all participating scientific personnel

1. Alexander N. Korotkov, Associate Professor, P.I.
2. Rusko Ruskov, postdoc
3. Valentin O. Turin, postdoc (not supported by this grant, though participated)
4. Qin Zhang, graduate student
5. Tao Gong, graduate student (supported for 3 months)
6. Junjie Yang, graduate student (supported for 3 months)

Report of Inventions

None